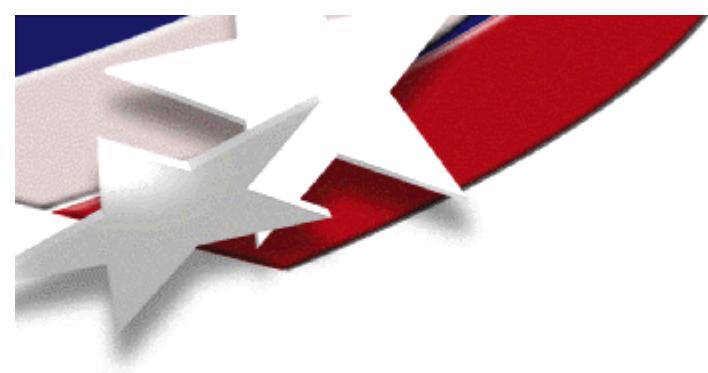


# Assessing and Improving System Performance

- *Power and Energy: Status of Array Design, Rating, Monitoring Methods*  
David King, Sandia
- *System Design and Performance Monitoring Tools*  
Mike Pelosi, Maui Solar Software
- *Predicted and Measured Performance for 10 Similar Systems in WI*  
Miles Russell, RWE Schott Solar
- *PV Module Testing and Modeling for Building Integrated Applications*  
Hunter Fanney, NIST



# **Power and Energy: Status of Array Design, Rating, Monitoring Methods**

**D. L. King, J. A. Kratochvil, and W. E. Boyson**  
**Sandia National Laboratories**  
**Albuquerque, New Mexico**  
**16 October 2003**



## Objective

**Develop PV array performance model with associated outdoor testing procedures and module database providing:**

- Accurate simulation for all PV technologies
- Module selection, array design, and system sizing
- Power (kW) and energy (kWh) analyses
- ‘Translation’ tool for installation, rating, diagnosis
- Real-time monitoring of array performance
- System optimization by application
- System performance ‘forecasting’

# Designing, Comparing, Optimizing, Rating, Monitoring



*Energy kWh*



## History of Sandia Model

- **1976 to 1990, years of module & array testing at Sandia, flat-plate and concentrators**
- **1991, initiated effort to develop and optimize outdoor test procedures for modules and arrays**
- **1995, initial version of our performance model, module testing, array testing with APS**
- **1998, performance model well validated, several publications, investigated by NIST**
- **1999, model adopted by Maui Solar for use in system design software, Sandia module database established**
- **2003, model & database used by manufacturers, integrators, utilities, consultants, CEC, etc.**
- **2004, assist integrators, others in implementing performance model and associated array testing**



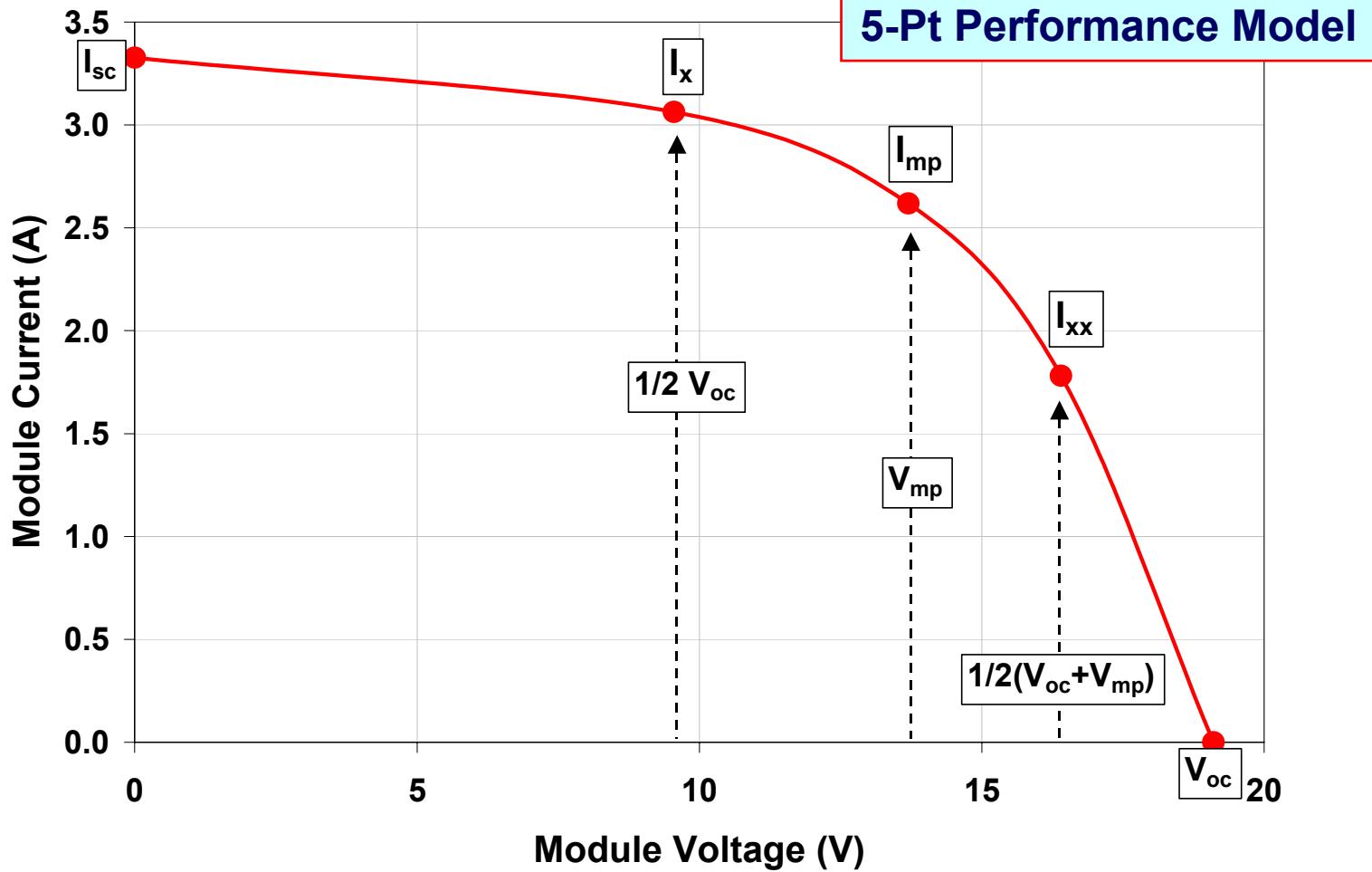
## Validation of Sandia Model

- **Outdoor characterization of over 1000 commercial modules since 1991**
- **1994 to 1999, test & model method applied to dozen different arrays, over 1 MW capacity**
- **1997, PVUSA/Endecon, detailed test & model comparisons for 5 large arrays, 4 technologies**
- **2000, NREL and Sandia, detailed year-long energy model comparisons for 5 module technologies**
- **2003, NIST and Sandia detailed comparison of outdoor testing procedures, 8 modules, rack mount and BIPV applications**

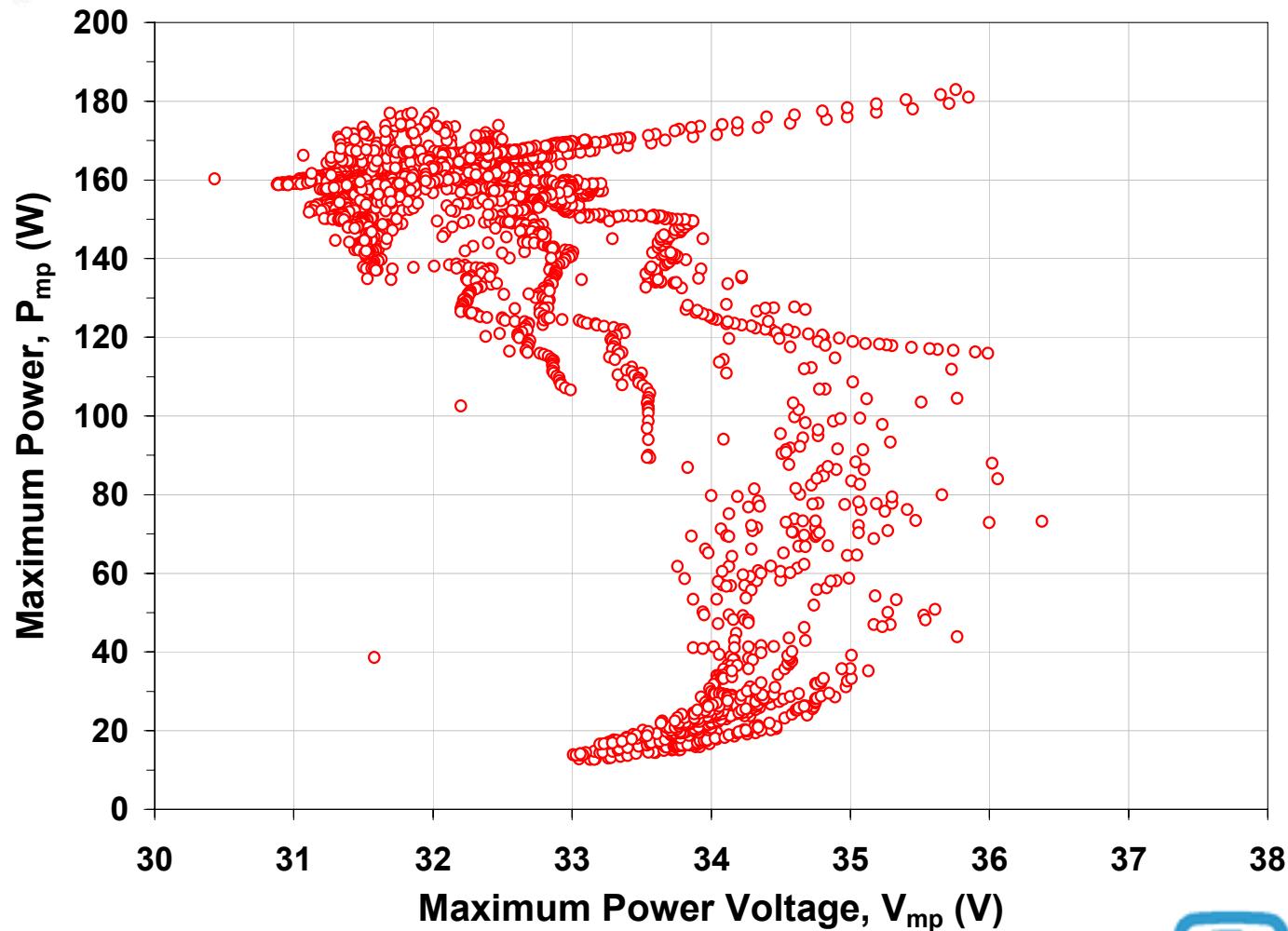
# Sandia Performance Model Accounts for All Major Influences

- **Irradiance components; beam and diffuse**
- **Temperature coefficients; Isc, Imp, Voc, Vmp**
- **Module orientation and tracking**
- **Technology specific cell physics**
- **Solar spectral variation versus air mass**
- **Angle-of-Incidence optical effects**
- **Site dependent solar resource and weather**
- **Thermal model using irradiance, ambient temperature, and wind speed**

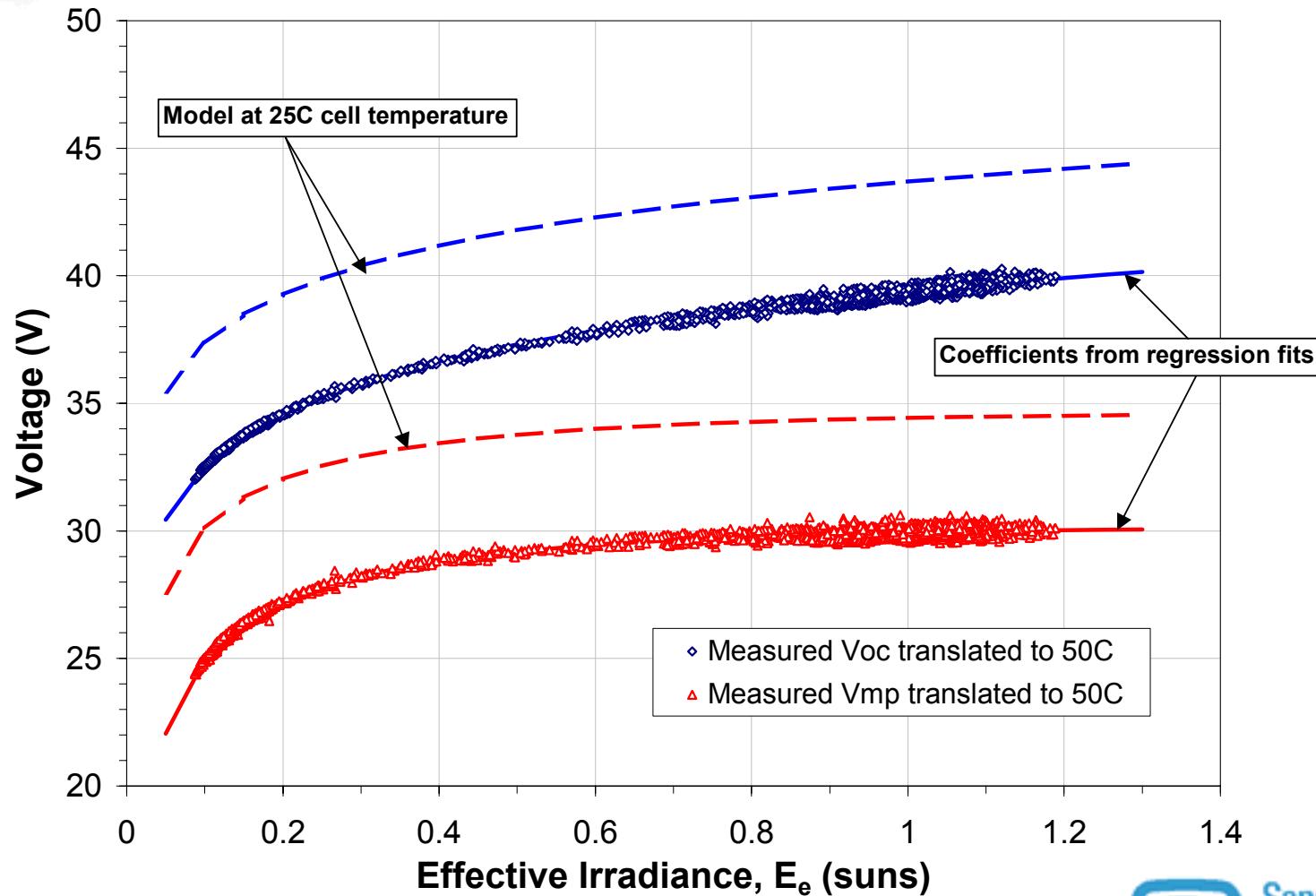
# Example: Sandia Outdoor Procedure



# Example: Sandia Outdoor Procedure

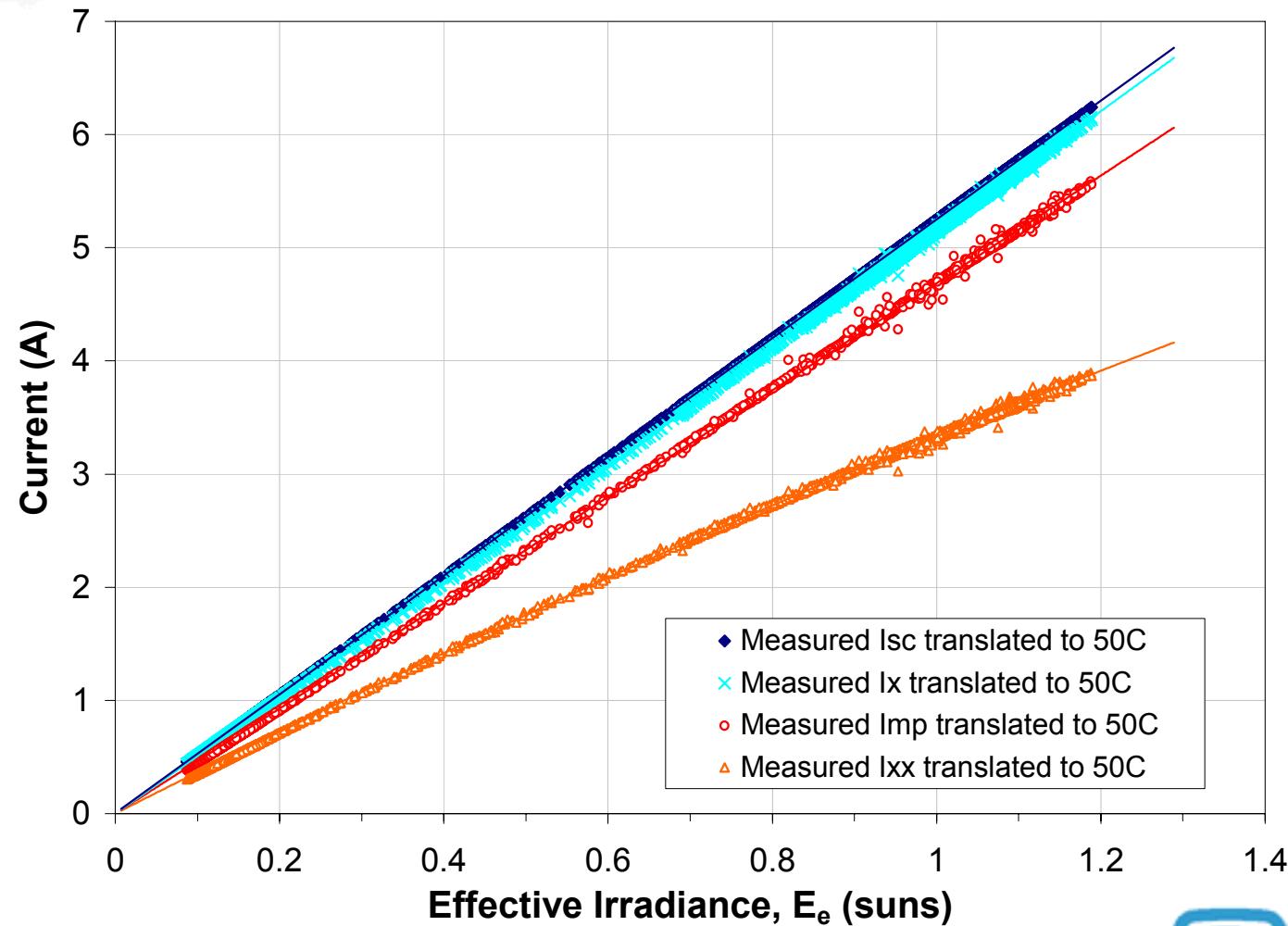


# Example: Sandia Outdoor Procedure



Sandia  
National  
Laboratories

# Example: Sandia Outdoor Procedure

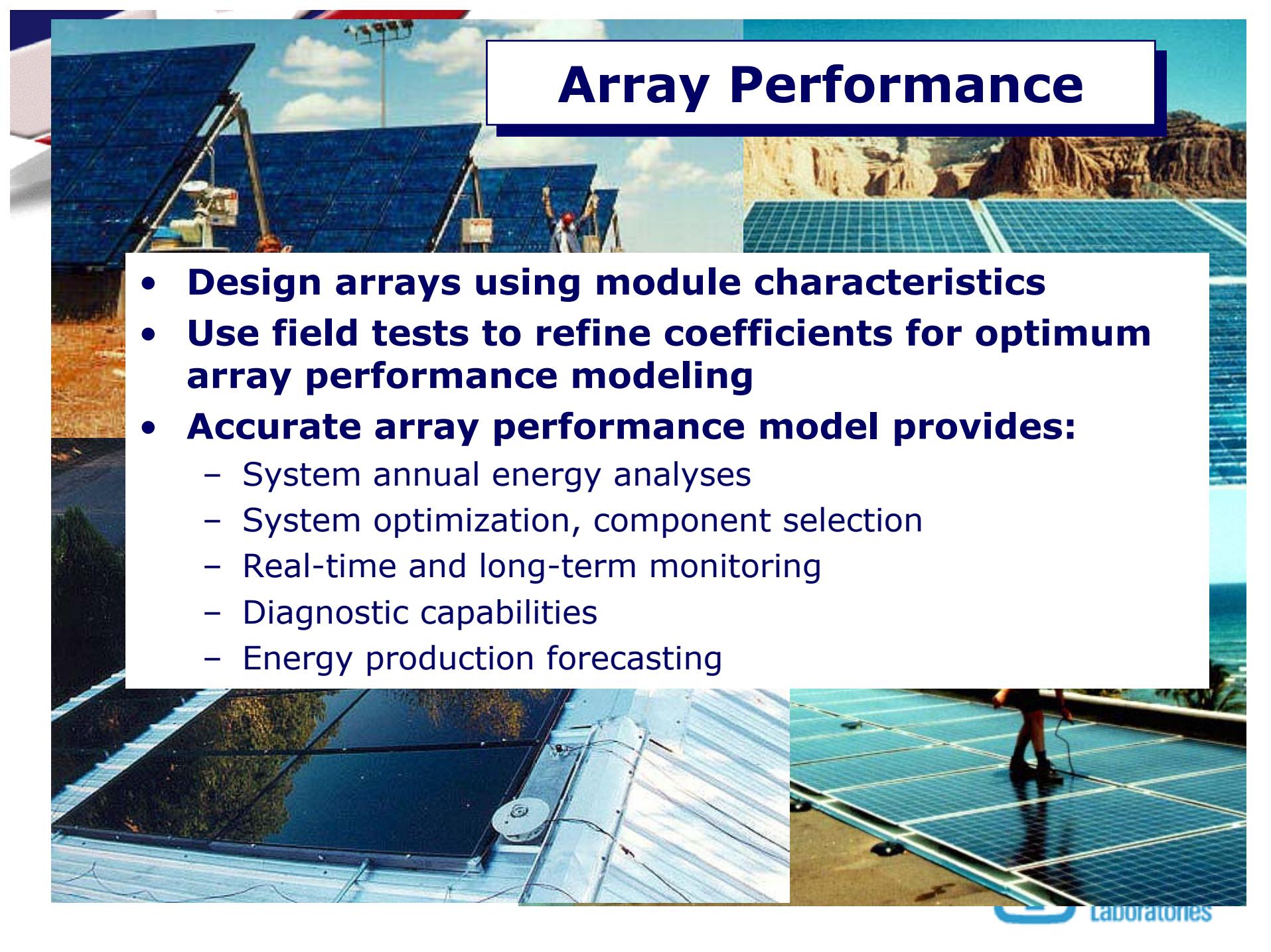


Model	Vintage	Area	Material	Series	Cells	Parallel	C-S	Isc	Voco	Impo	Vmpo	alsc	aImp	C0	C1	BVoco
12-PW 100 (95W)-Array	2001		10.78 m-c-Si		72	12	34.72	43.32	30.86	32.69	0.00045	-0.00015	0.945	0.055	-0.171	
8-BP275-Array	2000		5.04 c-Si		72	4	18.3	43.15	16.61	33.95	0.00033	-0.00032	0.979	0.021	-0.17	
8-KC80-Array	1990		5.14 m-c-Si		72	4	18	42.59	16.54	33.64	0.00085	0.00015	0.979	0.021	-0.1692	
ASE-100-ATF/17 (100)	1999 (E)		0.828 EFG m-c-Si		36	2	6.4	21.1	5.8	17.2	0.00078	0.0001	0.997	0.003	-0.076	
ASE-100-ATF/17 (85)	1999														-0.076	
ASE-100-ATF/17 (92)	1999														-0.076	
ASE-100-ATF/34 (100)	1999														-0.152	
ASE-100-ATF/34 (85)	1999														-0.152	
ASE-100-ATF/34 (92)	1999														-0.152	
ASE-300-DGF/17 (2.65)	1999														-0.0756	
ASE-300-DGF/17 (2.85)	1999														-0.0756	
ASE-300-DGF/17 (3.04)	1999 (E)		2.427 EFG m-c-Si		96	6	19.1	21.1	17.4	17.2	0.00092	0.00036	0.994	0.006	-0.0756	
ASE-300-DGF/50	1995		2.43 EFG m-c-Si		108	2	6.346	63.36	5.782	50.24	0.001	0.00034	0.994	0.006	-0.223	
ASE-300-DGF/50 (2.65)	1999 (E)		2.427 EFG m-c-Si		108	2	5.8	62	5.3	50	0.00092	0.00036	0.994	0.006	-0.227	
ASE-300-DGF/50 (2.85)	1999 (E)		2.427 EFG m-c-Si		108	2	6.2	62.5	5.6	50.5	0.00092	0.00036	0.994	0.006	-0.227	

# Module Performance Database

**World Status: 80+ module manufacturers, 400 + module sizes, dominantly mc-Si and c-Si, ~500 MW/yr production**

- **ASTM Standard Reporting Condition (SRC or STC) provides the basic reference condition**
  - **Outdoor test procedures provide performance coefficients required for all other conditions**
  - **Sandia database now has coefficients for 170+ modules, plus 5 arrays. Can't keep up with demand. Maui Solar working on a 'Wizard.'**



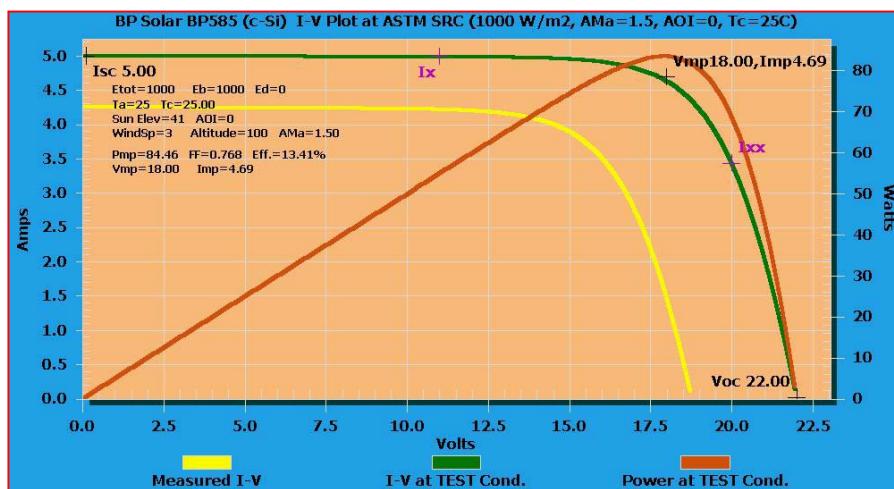
# Array Performance

- **Design arrays using module characteristics**
- **Use field tests to refine coefficients for optimum array performance modeling**
- **Accurate array performance model provides:**
  - System annual energy analyses
  - System optimization, component selection
  - Real-time and long-term monitoring
  - Diagnostic capabilities
  - Energy production forecasting



# Performance Model Provides the Best 'Translation' Tool

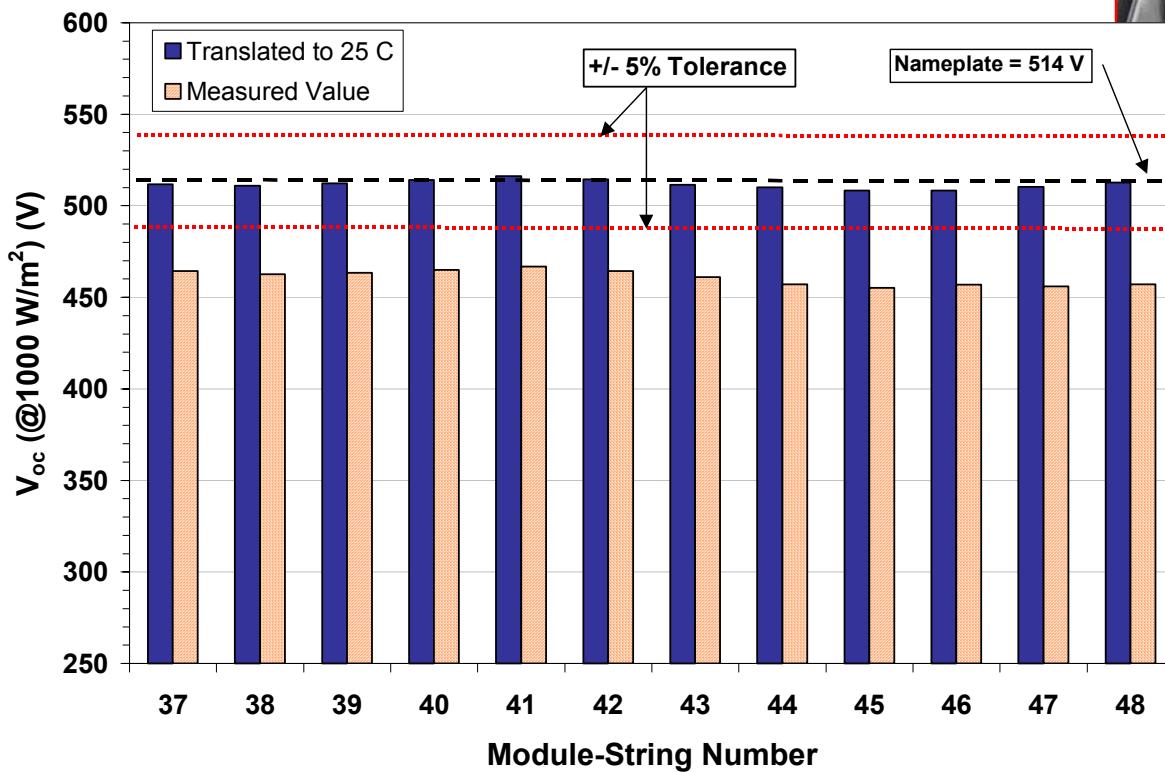
- Individual module I-V measurements
- Sub-array and array I-V measurements
- Module-string I-V or  $V_{oc}$  measurements
- Real-time operating current and voltage



IVTracer software  
by Maui Solar

# 'Translation' During Array Installation and Check Out

**Module-String  $V_{oc}$  Measurements**  
More diagnostic than typically recognized

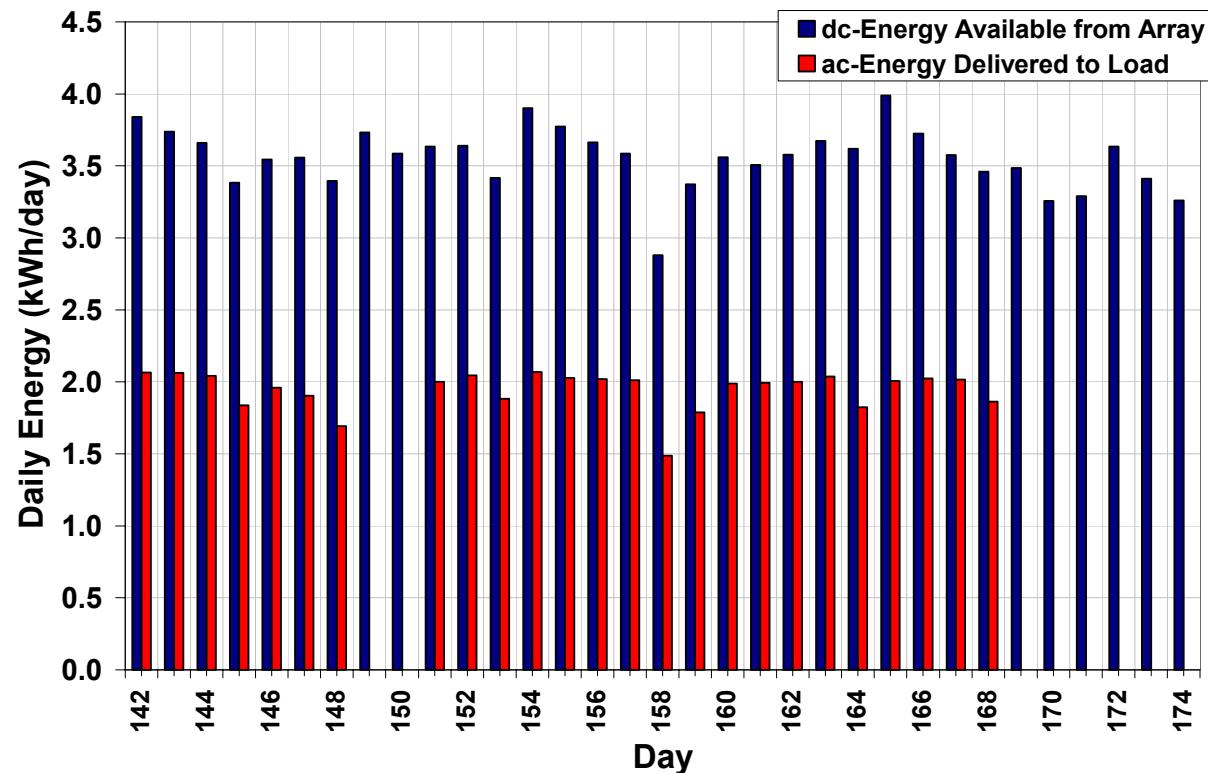


# Off-Grid PV System Optimization



## Systems R&D

30-day Procedure  
Predicted Energy  
Measured Energy



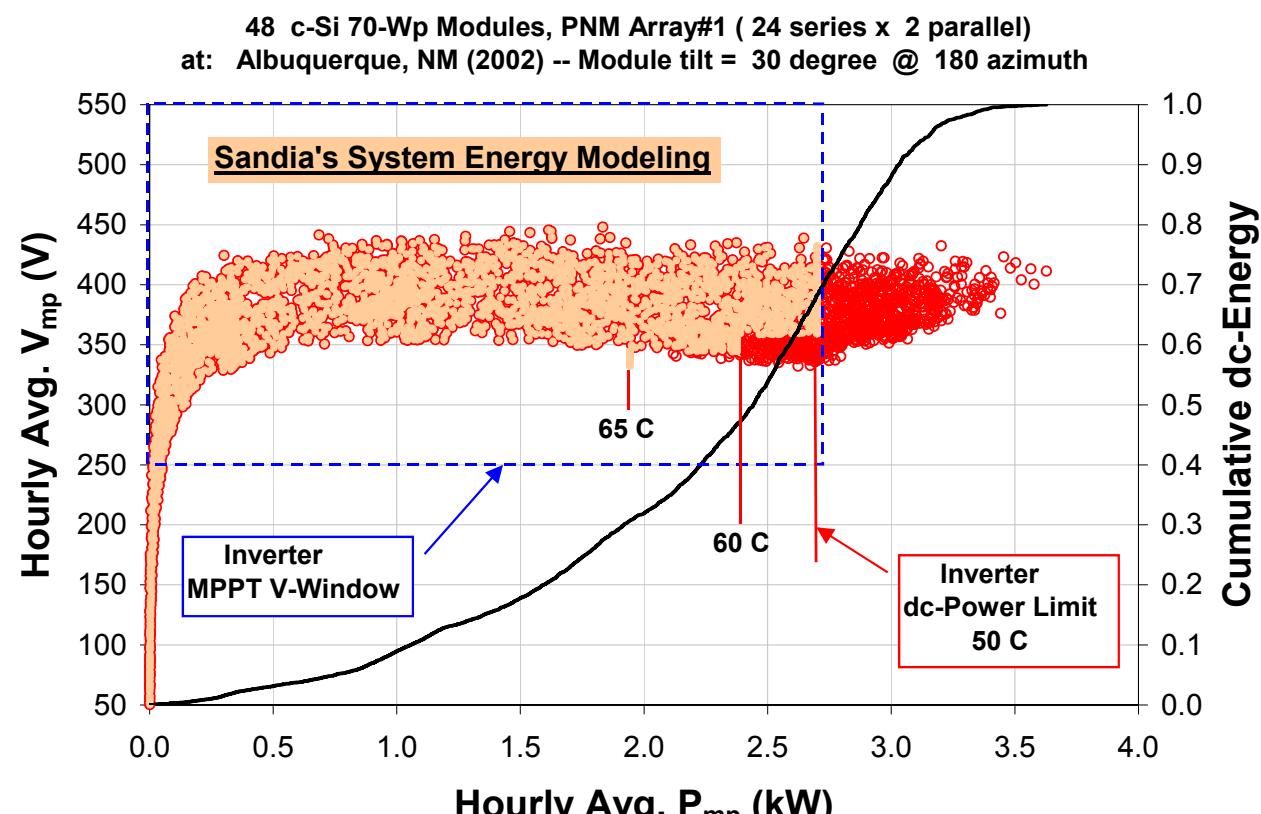
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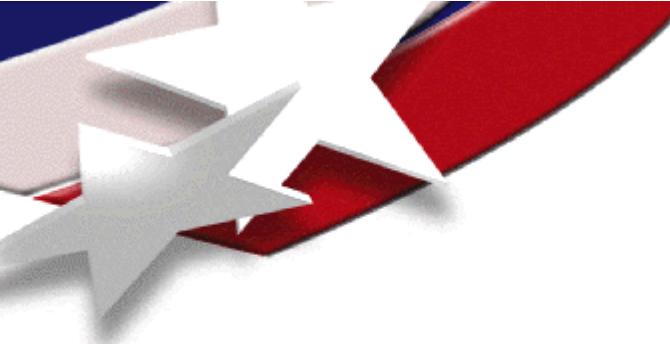
# Grid-Tied PV System Optimization



## Systems R&D

- Site dependent solar and weather data
- Array performance model for entire year
- Component selection and matching
- Long-term monitoring
- Real-time monitoring



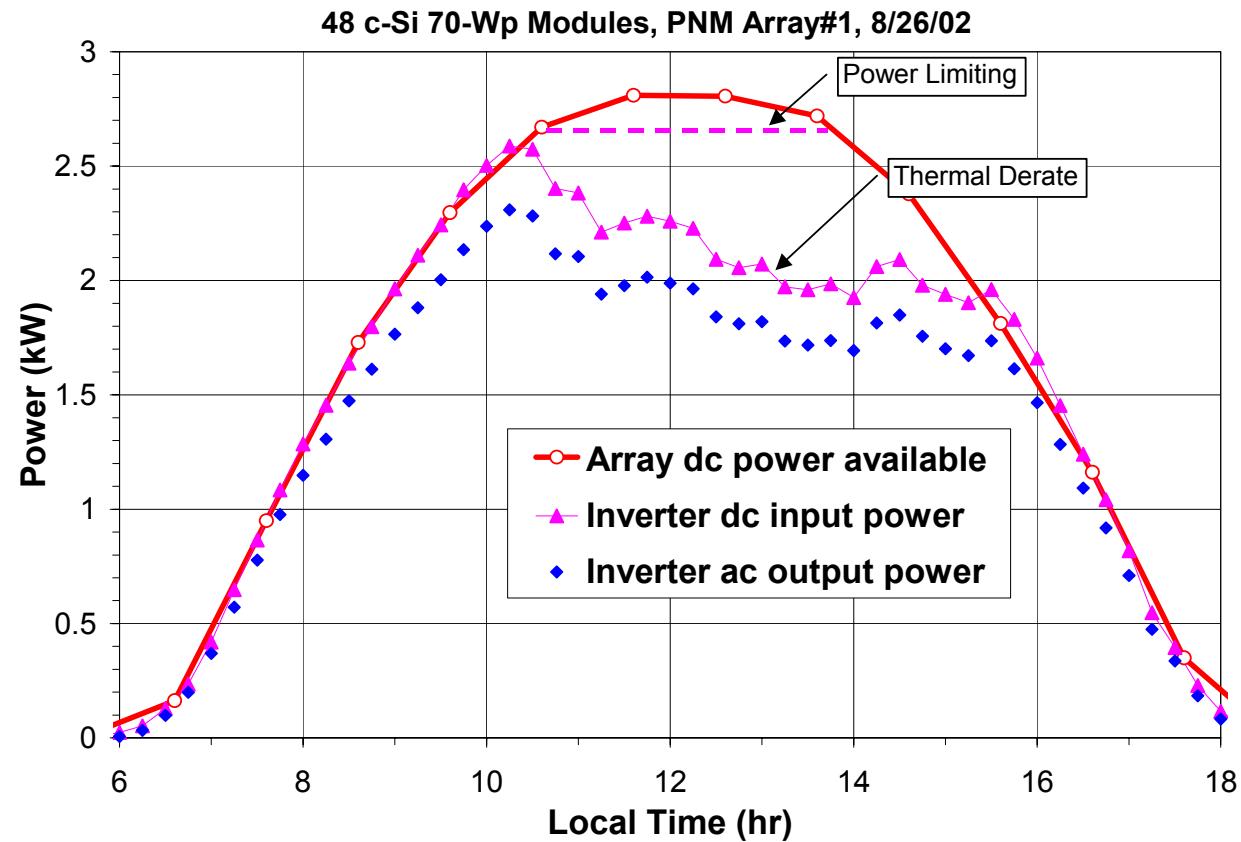


## Conclusions

- **Successful design, testing, and marketing are dependent on accurate performance models for energy production**
- **Collaborative efforts with APS, Endecon, Maui Solar, NIST, NREL, and RWE Schott Solar have resulted in high level of confidence in array performance model**
- **More effort is still required to model performance of other system components; inverters, charge controllers, batteries, as well as economics, degradation rates, etc.**

# Daily Monitoring of Array and System Energy Production

Model + DAS  
Real-time Monitoring  
Long-term Monitoring  
Predicted vs. Actual  
Remote Control



# Off-Grid PV System Optimization



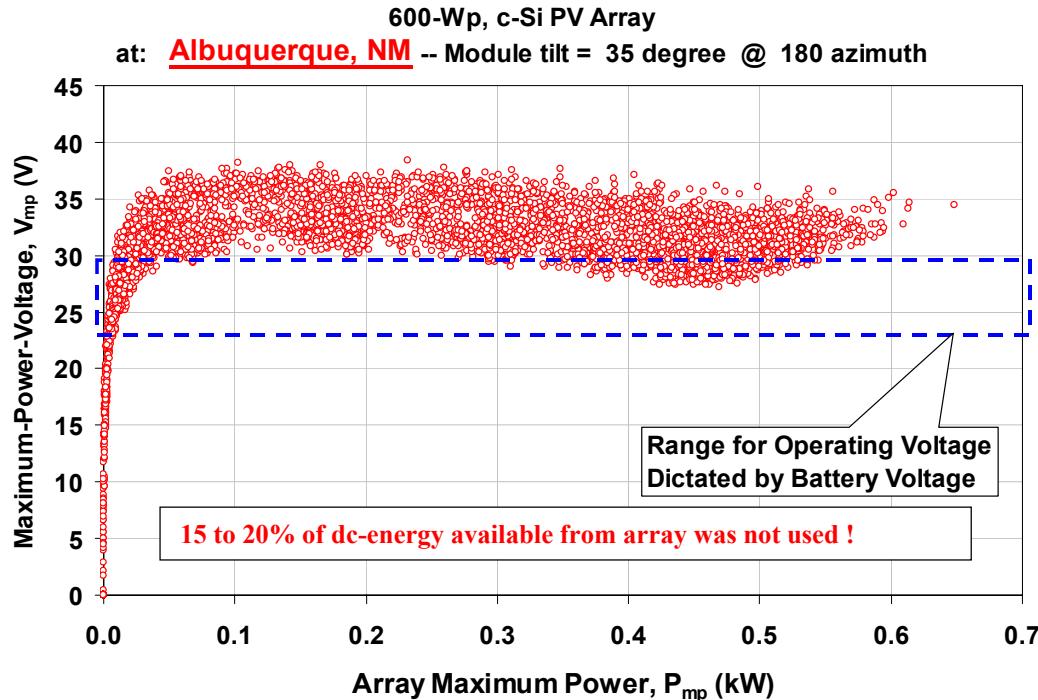
## Systems R&D

30-day Procedure

Predicted vs. Actual

Reliability

Safety



# System Energy Modeling

**Successful system design, optimization, monitoring  
requires model with:**

- Site solar resource and weather data
- Array configuration and mounting method
- Electrical, thermal, optical characteristics for modules
- Provisions for performance, interactions, and aging of all BOS components

